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Optical Manipulation of Ultracold Atoms

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Motivation: It is well known that ultracold atoms ($T < 1$ milliKelvin) are promising candidates for next-generation inertial sensors and magnetometers. An “atom interferometer” measures accelerations and rotations in much the same way as does a laser-based interferometer, except that the recorded interferograms are due to matter wave interference rather than optical interference.

Large laboratory-based atom interferometers using thermal atom beams have demonstrated unparalleled performance, but the most promising path to making such technology practical is to use ultracold atoms: unlike room temperature atoms, cold atoms can be guided along controlled trajectories, analogous to fiber optics for light. The roles of matter and light are reversed—whereas material guides photons in fiber optics, photons guide atoms in atom optics. To realize high sensitivities with cold atoms, we must 1) obtain a large flux of cold atoms and 2) guide atoms coherently in atom waveguides. Our group is working on these issues using optical techniques with cold atoms derived from a “magneto-optical trap” that contains roughly 10^8 rubidium atoms at a temperature of $10\ \mu\text{K}$ and density of 10^{11} atoms/cm³.

Background: When an atom is exposed to an optical field, the force acting on the atom is proportional to the intensity gradient. Laser fields tuned above an atomic resonance repel atoms from regions of high intensity toward low intensity. Such “blue-detuned” atom manipulation, therefore, helps preserve coherence by lowering spontaneous emission events. One

challenge to using blue-detuned traps and guides is the requirement of creating volumes or channels in space bounded by regions of high intensity, such as a hollow laser beam. Because lasers generally produce Gaussian modes, they cannot guide atoms with blue-detuned light without modification.

Cold Atom Transport: We have developed tools for delivering a large flux of atoms through hollow optical fibers.¹ Figure 7(a) shows a schematic of a hollow optical fiber developed in our lab, designed to transfer cold atoms through its vacuum core from a source chamber of trapped cold atoms to a destination chamber. Blue-detuned light is coupled into the annulus of the fiber, and the evanescent field that extends into the core is sufficient to prevent atoms from sticking to the fiber walls. In our technique, light is coupled through the sides of the fiber using micro-prisms embedded into the cladding (Fig. 7(b)). The fiber ends are coated so that light only interacts with the atoms during transport.

Dark Optical Traps: We have also generated guides for cold atoms using spatial light modulation of freely propagating beams. By altering the phase profile across a Gaussian beam with a spatial light modulator, we create hollow laser beams (inset of Fig. 8(a)). Crossing two hollow laser beams provides full 3D confinement of the atoms in traps as small as a few tens of microns in diameter. Figure 8(b) shows a time sequence of atoms expanding into a single hollow beam, and full confinement with crossed beams is shown in Fig. 8(c). We have shown that, because the atoms are confined to the dark and are minimally exposed to the guiding light, scattering rates can be reduced by up to two orders of magnitude over conventional traps based on red-detuned light.²

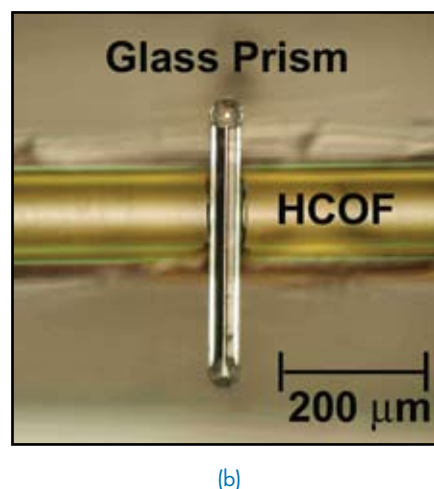
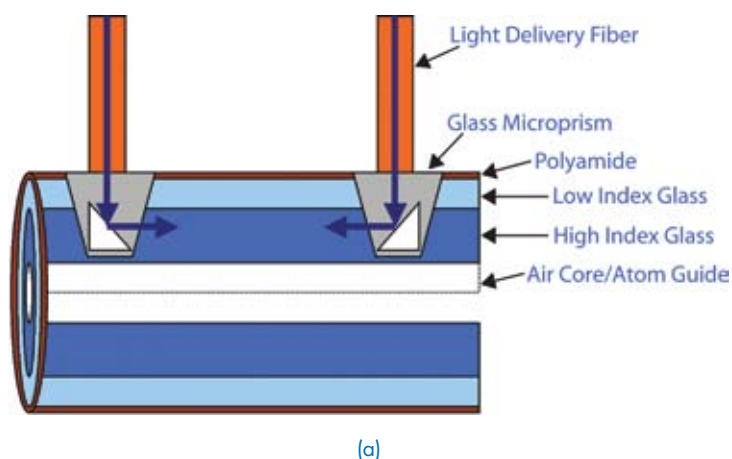
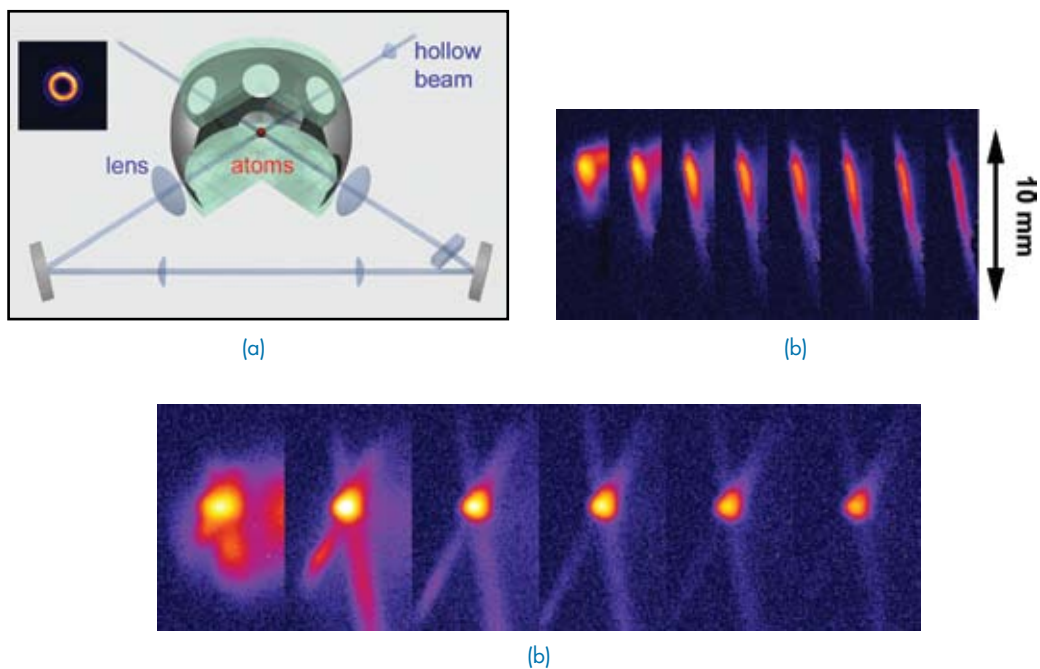
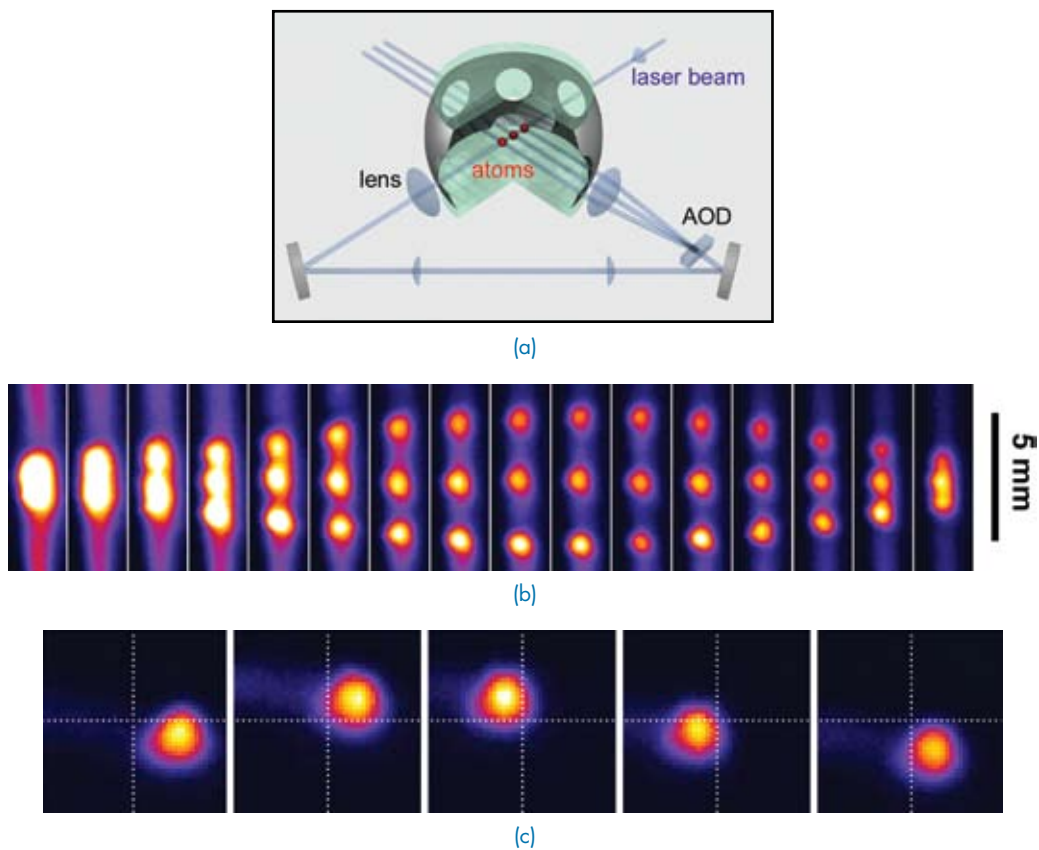


FIGURE 7
(a) Side-illuminated hollow core fiber. (b) Image of glass prism embedded in hollow core optical fiber (HCOF).

**FIGURE 8**

(a) Hollow beams intersect in the center of a vacuum chamber containing a magneto-optic trap of cold atoms. Inset: 200 μm diameter hollow beam formed by spatial light modulation. (b) Cold atoms expanding into a single hollow beam over 50 ms. (c) Cold atoms confined in crossed hollow beams over 100 ms.

**FIGURE 9**

(a) Spatial locations of atoms are controlled by acousto-optic deflection (AOD). (b) Atom cloud split into three independently controlled clouds separated by 5 mm. Images are taken every 2 ms. (c) Atoms moved in a 2 mm diameter circle using a second AOD before the chamber. Images are taken every 10 ms.

Dynamic Manipulation of Atoms: These confining traps can also be manipulated spatially. Figure 9(a) shows a schematic of our current apparatus, in which the intersection point of the crossed hollow beams is controlled with acousto-optic deflectors (AODs). These deflectors scan the beam by changing the RF drive frequency, so the spatial positions can be scanned rapidly (>50 kHz) with excellent resolution. Furthermore, the AODs can be driven with multiple drive frequencies simultaneously, generating several atom traps in parallel that can be independently controlled. We have recently demonstrated splitting of the traps into three individually controlled sites (Fig. 9(b)).³ Using multiple AODs, we have moved the atoms in 2D trajectories (Fig. 9(c)).

Summary: We have demonstrated spatial control of ultracold atoms using all-optical techniques that preserve atom coherence. In addition to applications in inertial sensing, such spatial sampling by small, dense atom clouds may allow spatially resolved magnetometry with resolutions not possible with current alkali magnetometers. The techniques shown here may be combined with magnetic atom-guiding techniques, which are most commonly pursued for these applications. Despite extensive research in cold atom physics for over two decades, interest in both applications and fundamental research derived from it continues to grow.

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